Convective and non-convective mixing in AGB stars

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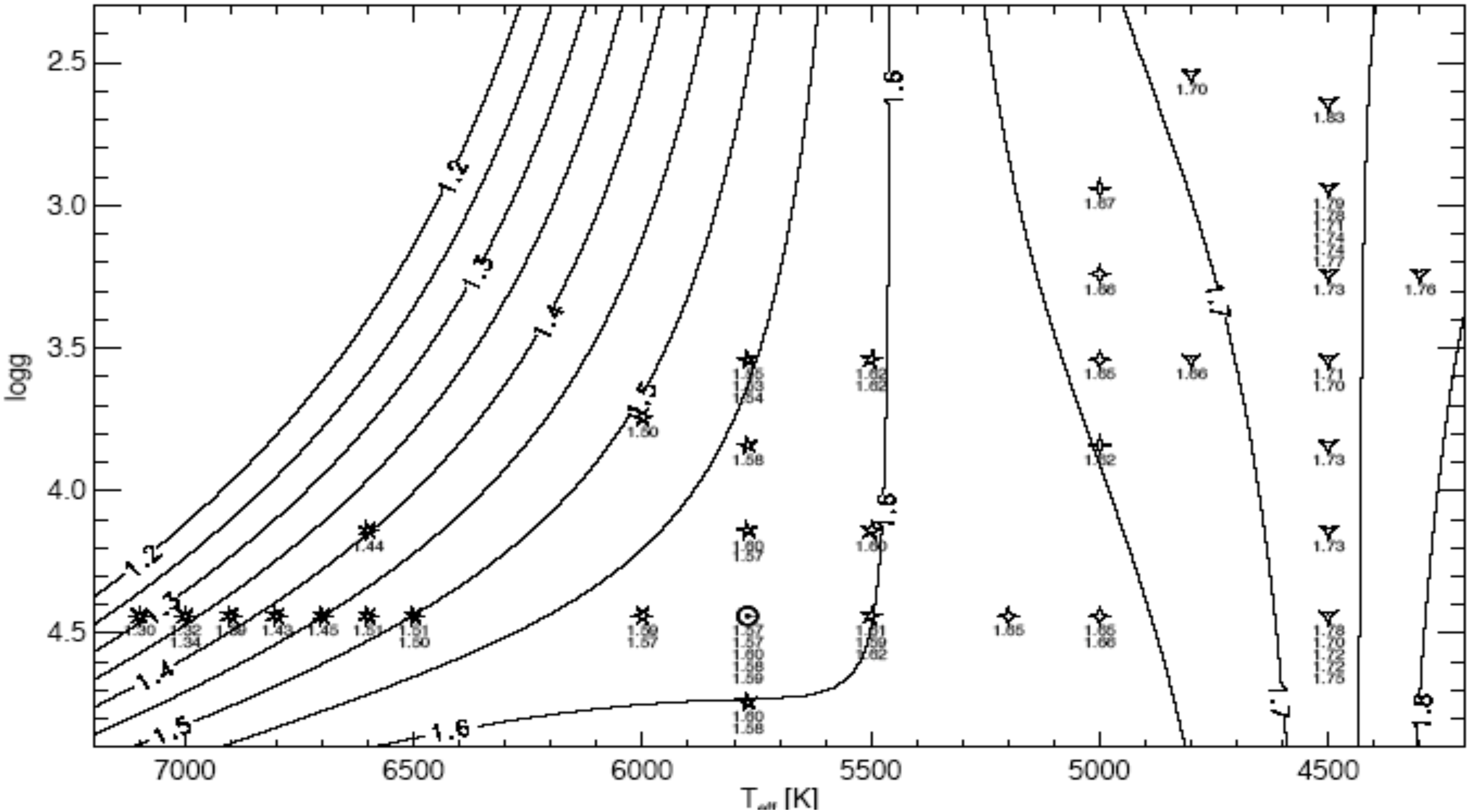
Variation of mixing length parameter:

Calculated from a grid of RHD convective envelope models for sun-like stars

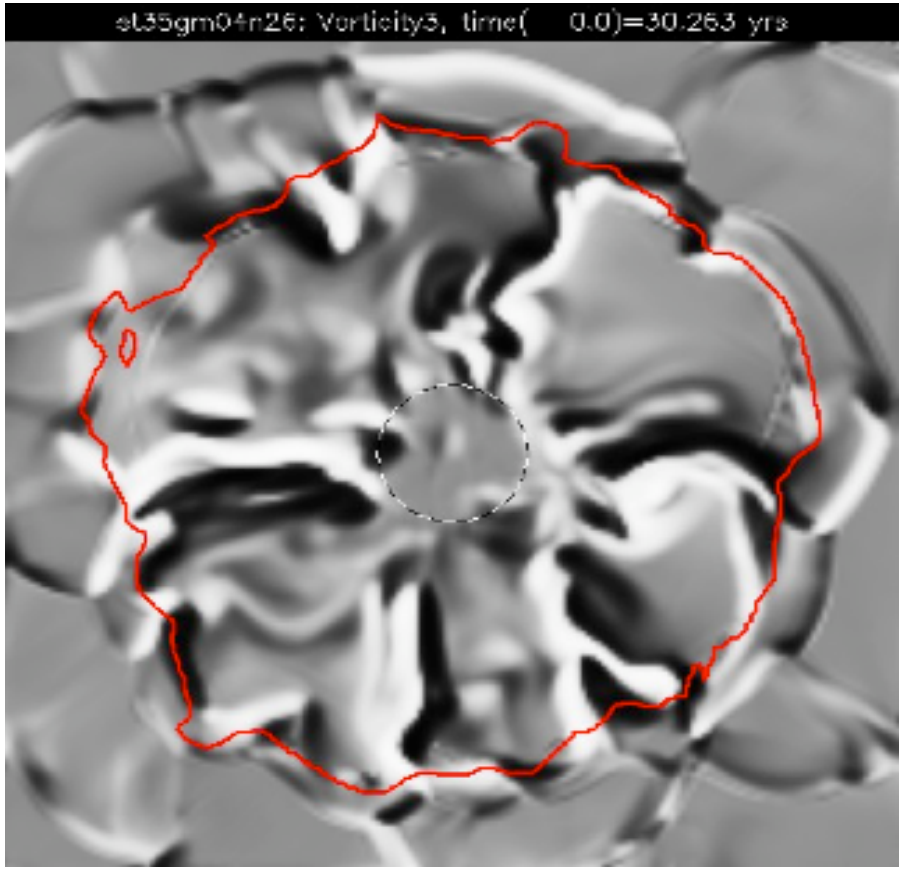


Ludwig etal 1999

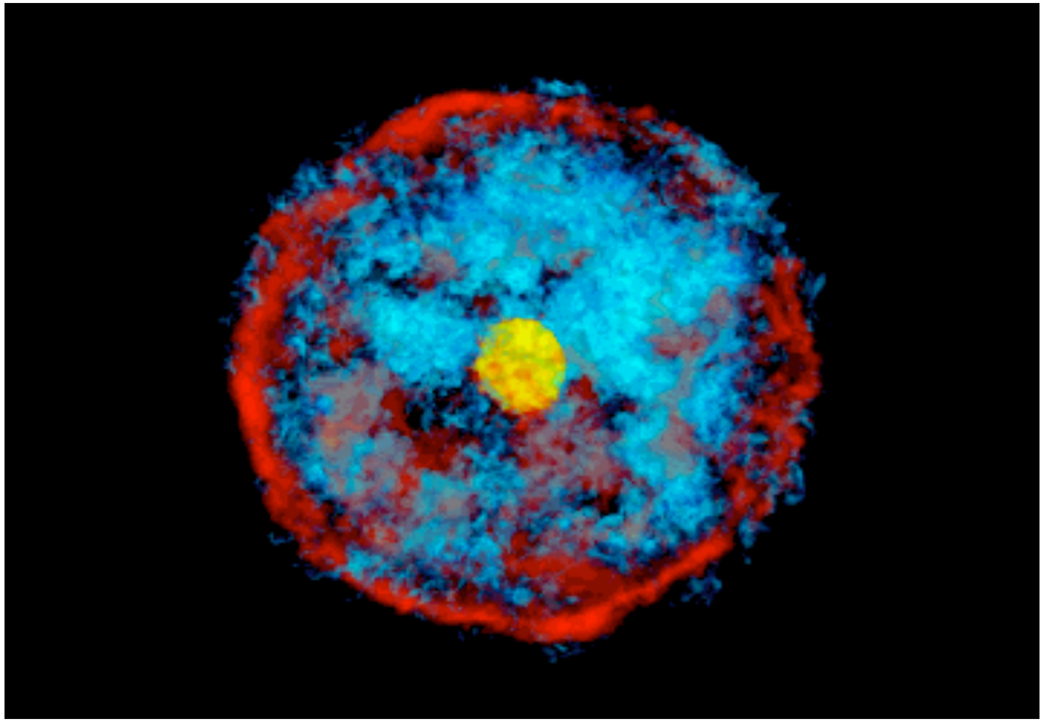
3D hydro simulations of AGB convective envelopes

Simulations by Bernd Freytag (left) and Paul Woodward and David Porter (right)

Vorticity:



Temperature fluctuations:



Porter & Woodward 2000, ApJS 127, 159

http://www.astro.uu.se/~bf

http://www.lcse.umn.edu/research/RedGiant

Multi-dimensional hydrodynamics simulations of He-shell flash convection

Goals:

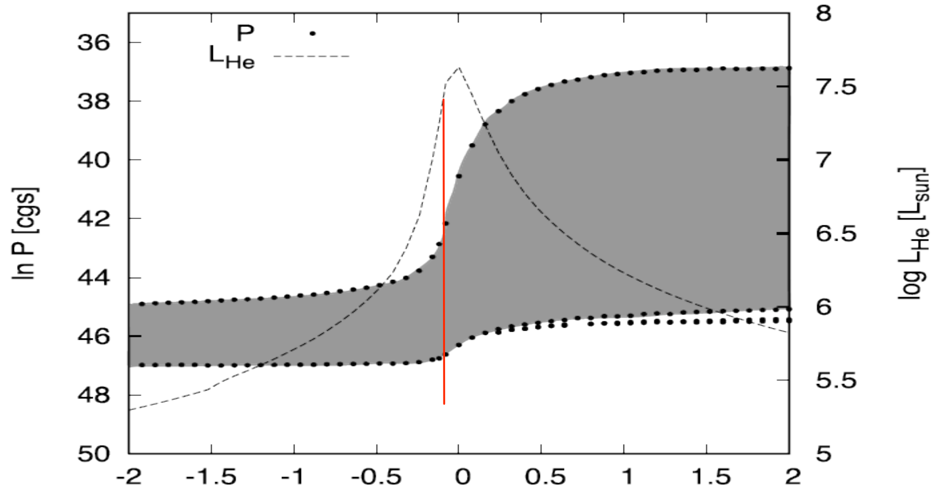
- Topology of He-shell flash convection - how does it look like?
- Velocity distribution for short-lived T-dependent s-process branchings (e.g. ^{128}I, Reifarth etal. 2004, ApJ)
- Entrainment (mixing across convective boundaries): there is a continuous range from classical overshooting to gravity wave turbulent mixing
- Next step: H-ingestion into He-shell flash (metal poor AGB stars, post-AGB born-again stars)

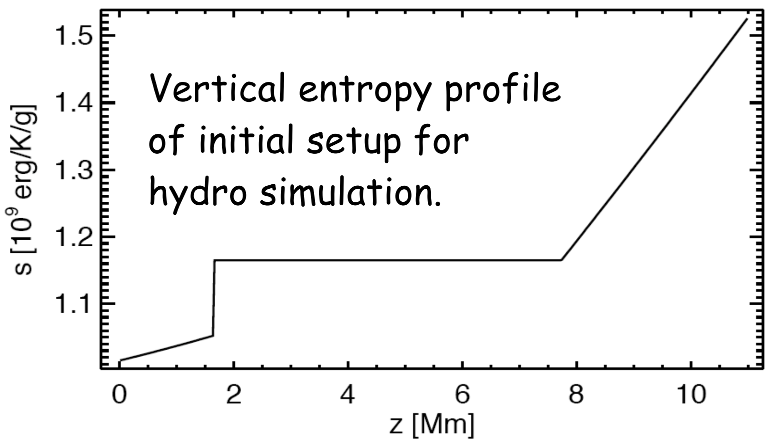
Collaborators: Bernd Freytag, Robert Hueckstaedt, Frank Timmes

Herwig etal 2006, ApJ 642, 1057, Freytag etal. 2006, in prep.

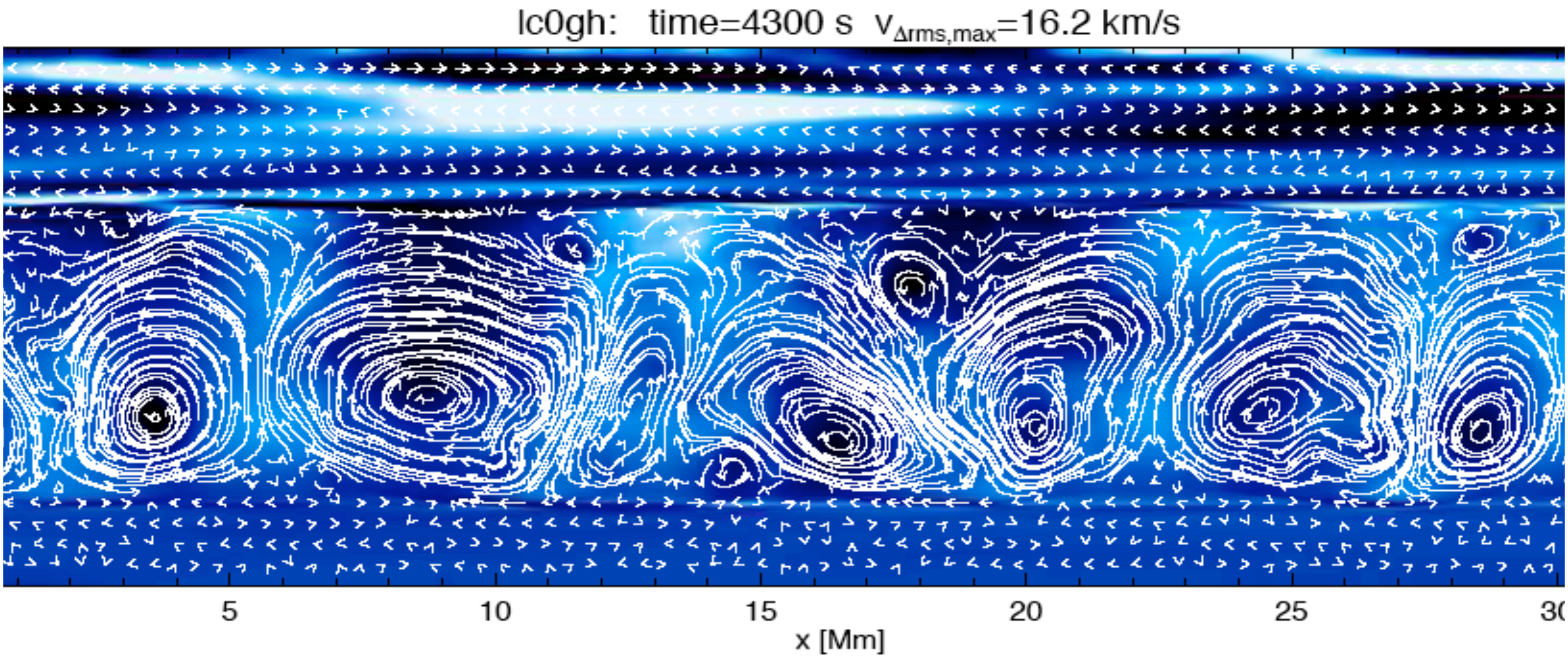
Setup, code, initial conditions

•2D and 3D hydrodynamics simulations of a short duration (~20ksec) of He-shell flash convection at a time just before the peak of He-flash
•Explicit, Eulerian, compressible grid code RAGE
•Initial conditions: piecewise polytropic stratification with gravity that closely resembles the actual conditions in a specific $2M_{\odot}$, Z=0.01 thermal pulse model



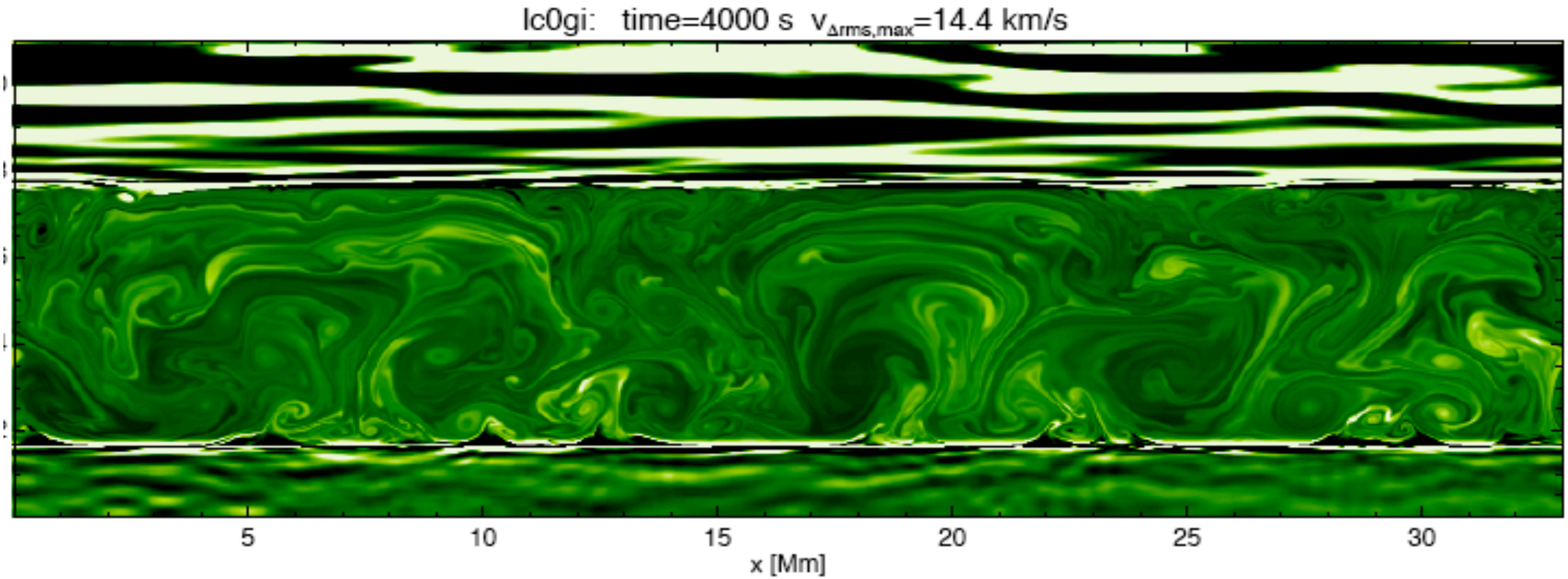


Flow pattern



Pressure fluctuations with pseudo-streamlines overplotted, 2D, 1200x400, enhanced heating (30x) (lc0gh)

High-resolution run



2D entropy fluctuations (2400x800), realistic heating rate

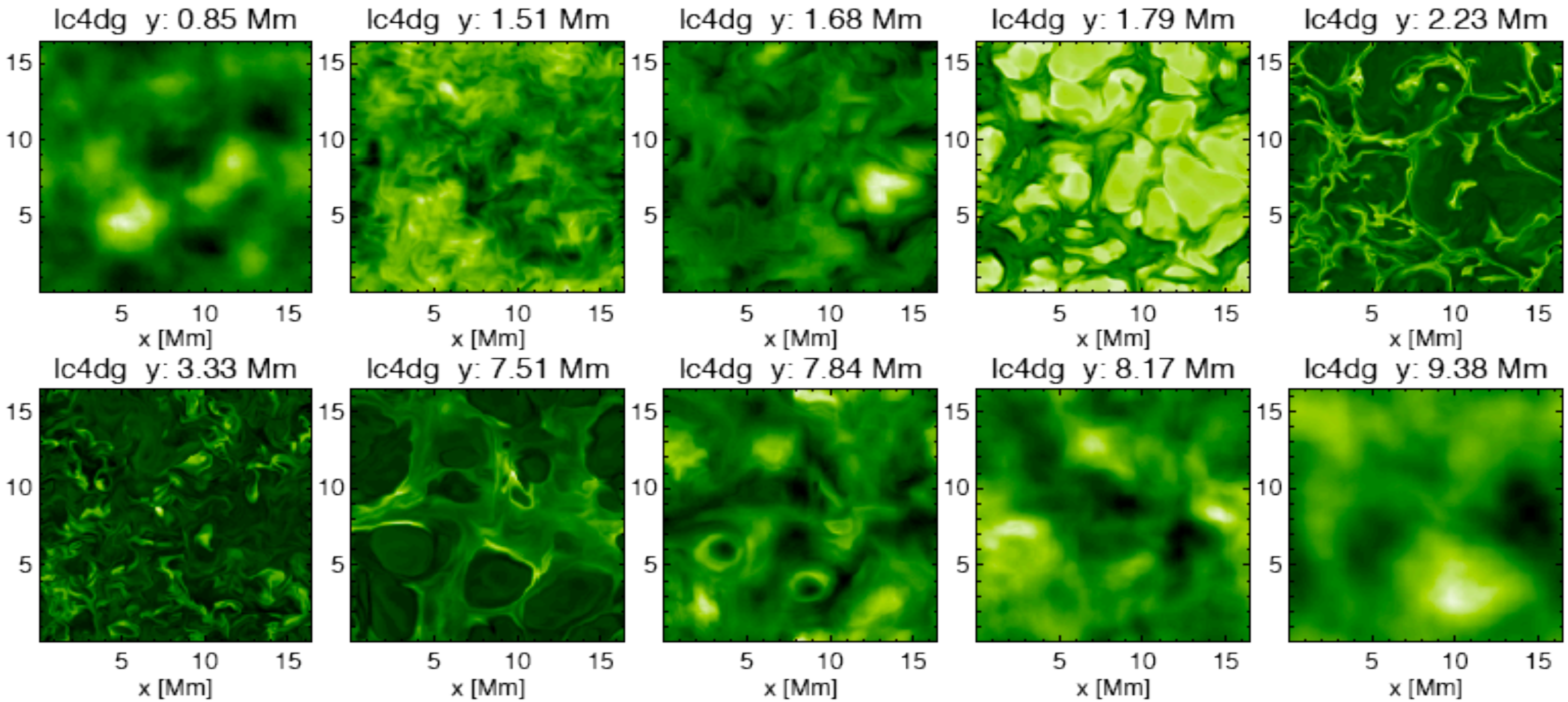
Courant time scale at this resolution: ~3*10^{-3}sec -> 1.6M cycles

Movie 2D

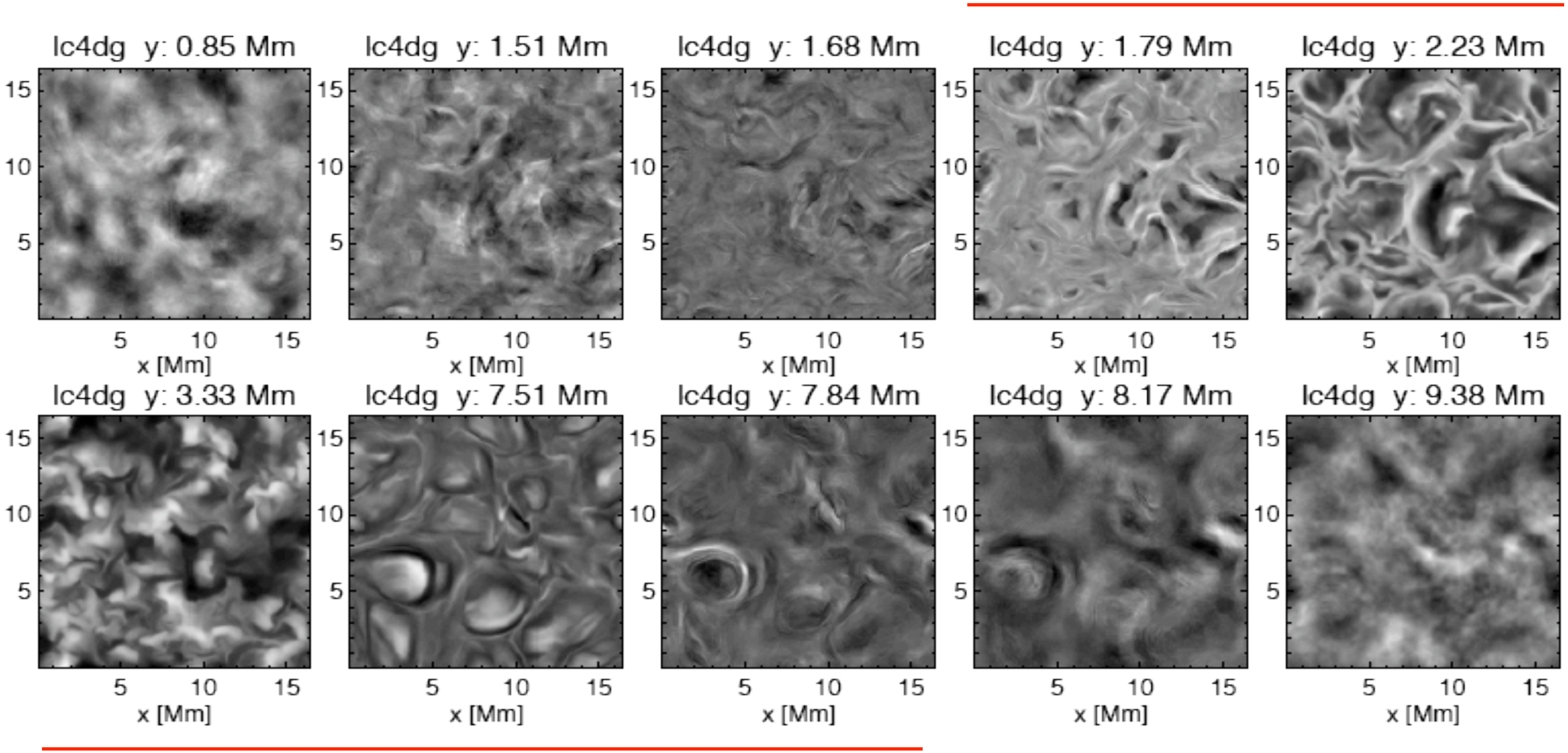
Insert here movie lc0gh_ds.mpg.

Entropy fluctuations, 2D, 1200x400, realistic heating (lc0gh)

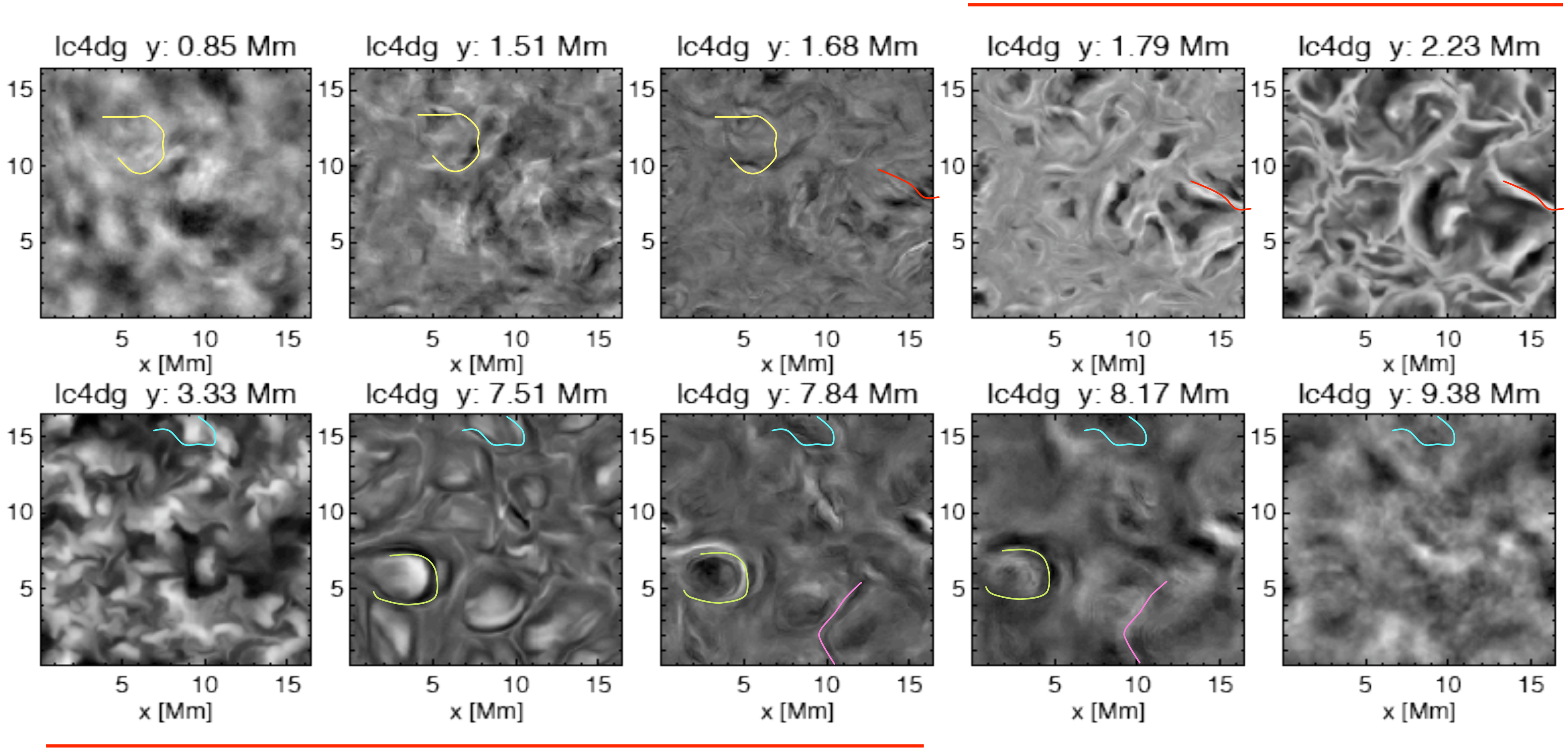
3-dimensional simulation: 300^2x200, enhanced heating (lc4dg)
Horizontal slices of entropy fluctuations



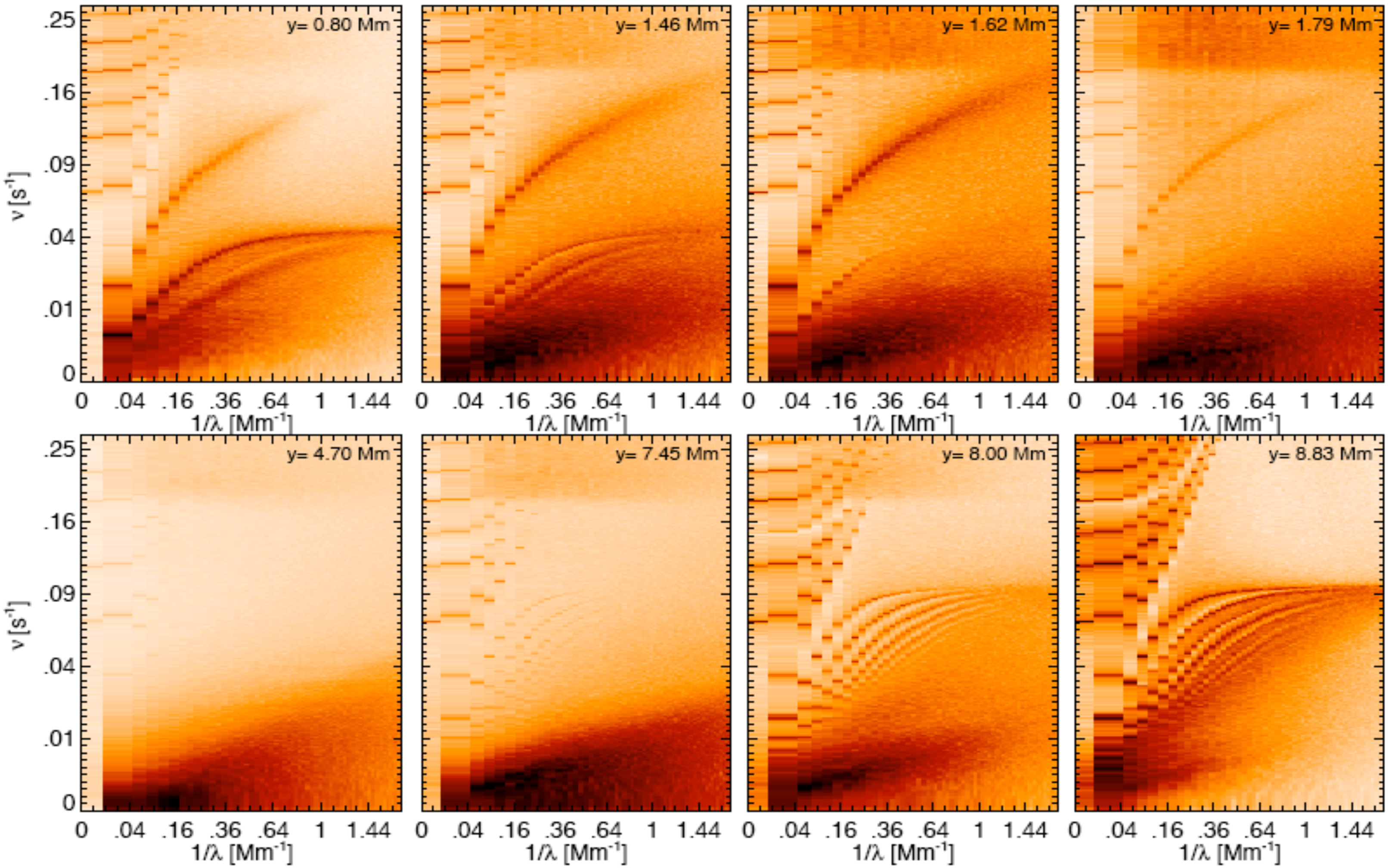
3-dimensional simulation: 300^2x200, enhanced heating (lc4dg)
Horizontal slices of vertical velocity



3-dimensional simulation: 300^2x200, enhanced heating (lc4dg)
Horizontal slices of vertical velocity

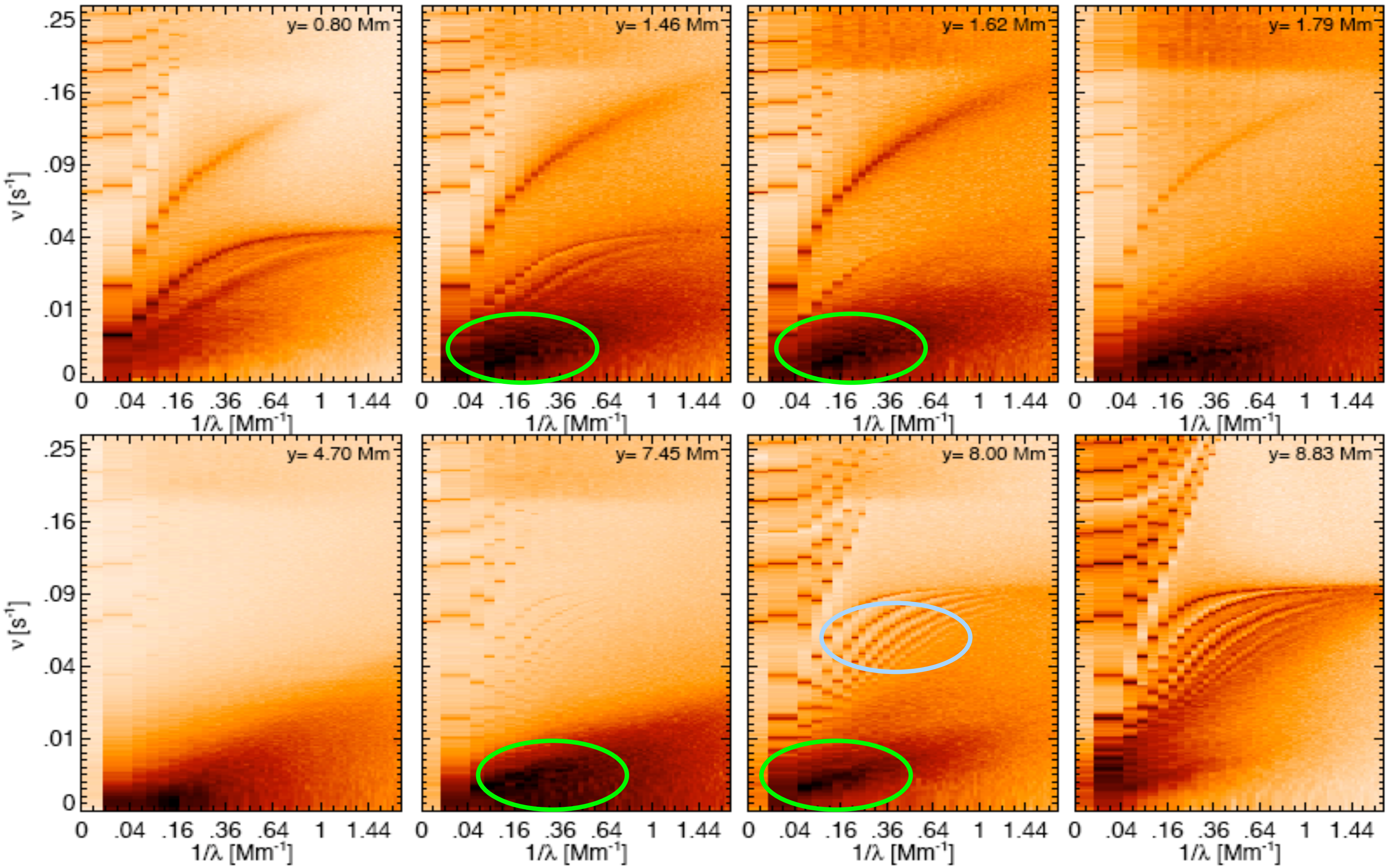


Oscillation analysis



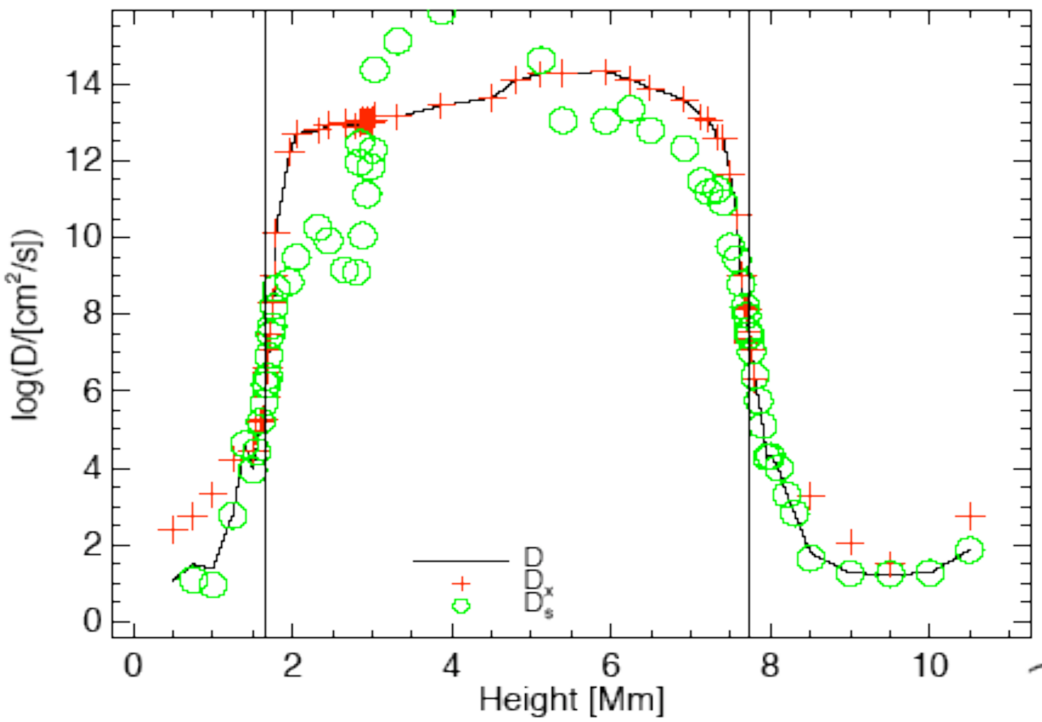
k-ω diagrams for various heights of benchmark run lc0gg

Oscillation analysis

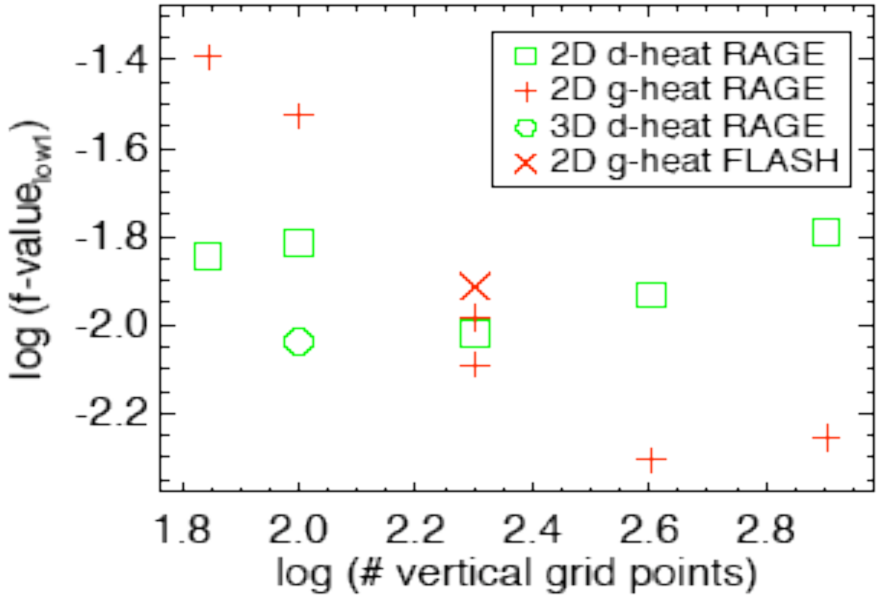


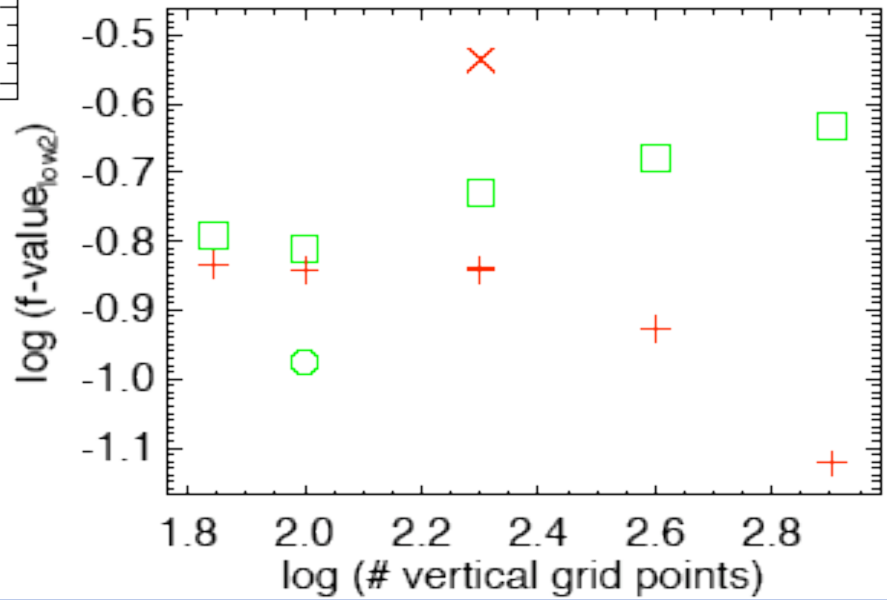
k-ω diagrams for various heights of benchmark run lc0gg

Mixing of He-shell Flash Convection



Diffusion coefficient reflecting hydrodynamic mixing (Freytag & Herwig, 2006, in prep).





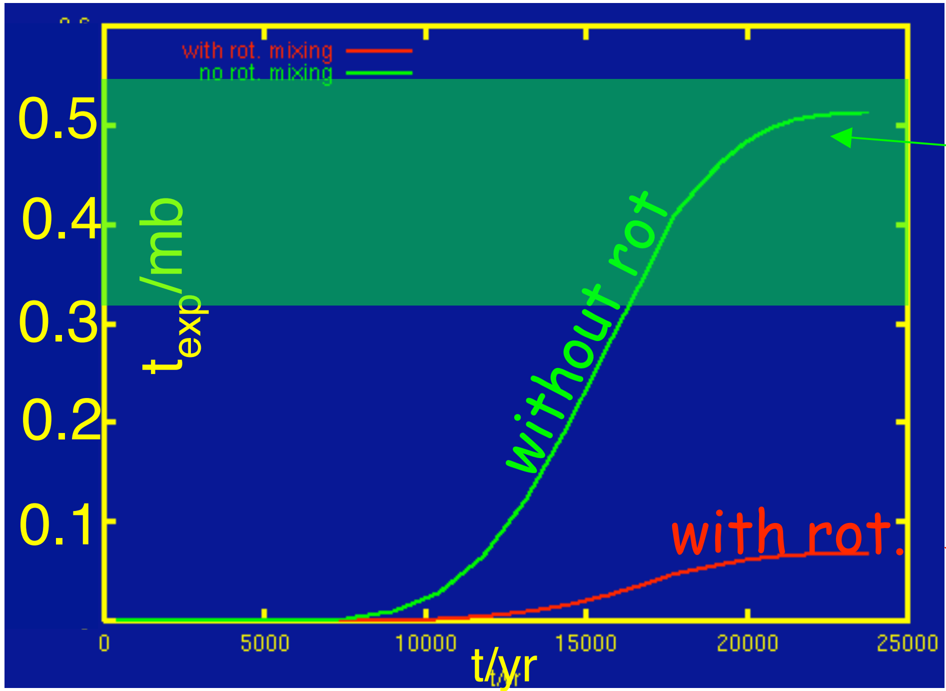
$f_{top} \sim 0.10$

$f_{bot,1} \sim 0.01$

$f_{bot,2} \sim 0.14$

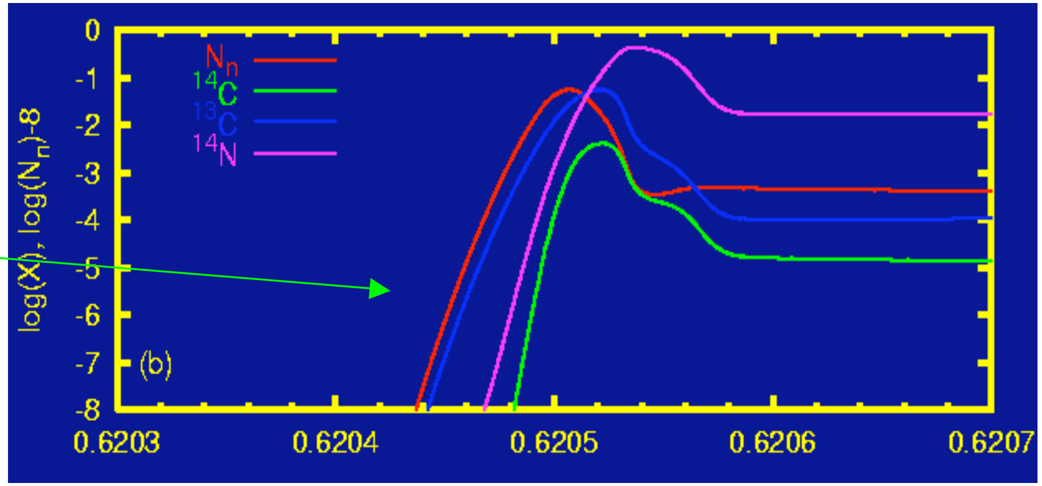
s-process in rotating AGB Stars

Neutron exposure in s-process production site:

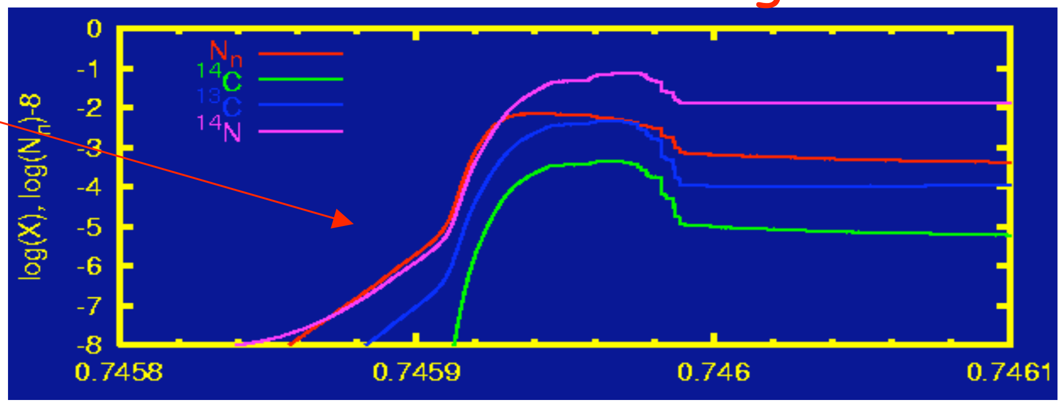


Herwig etal (2003), Siess etal. (2004)

overshoot mix, no rot mix

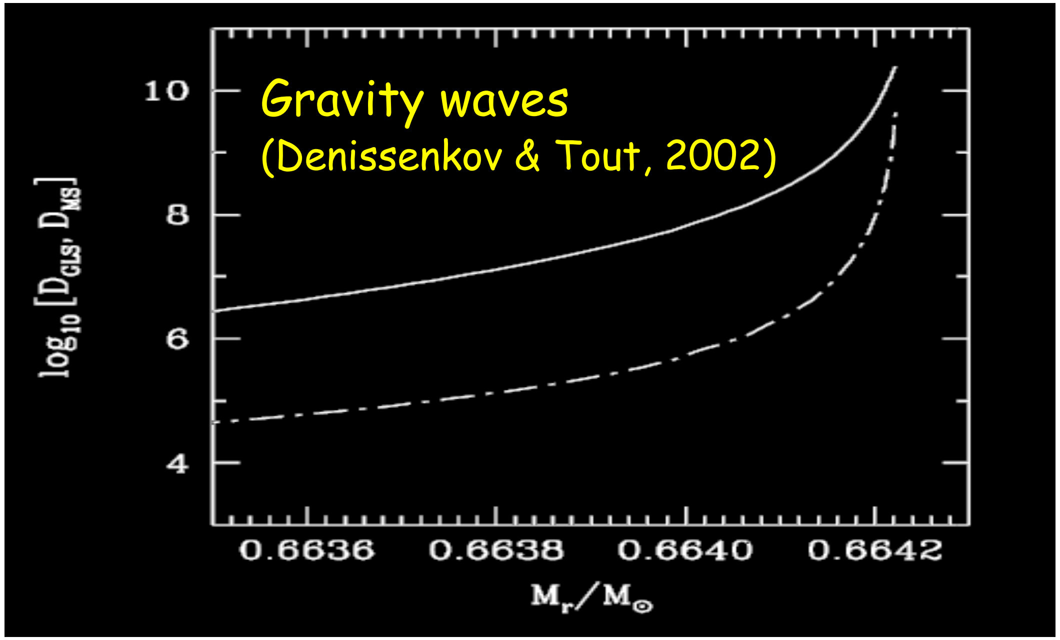


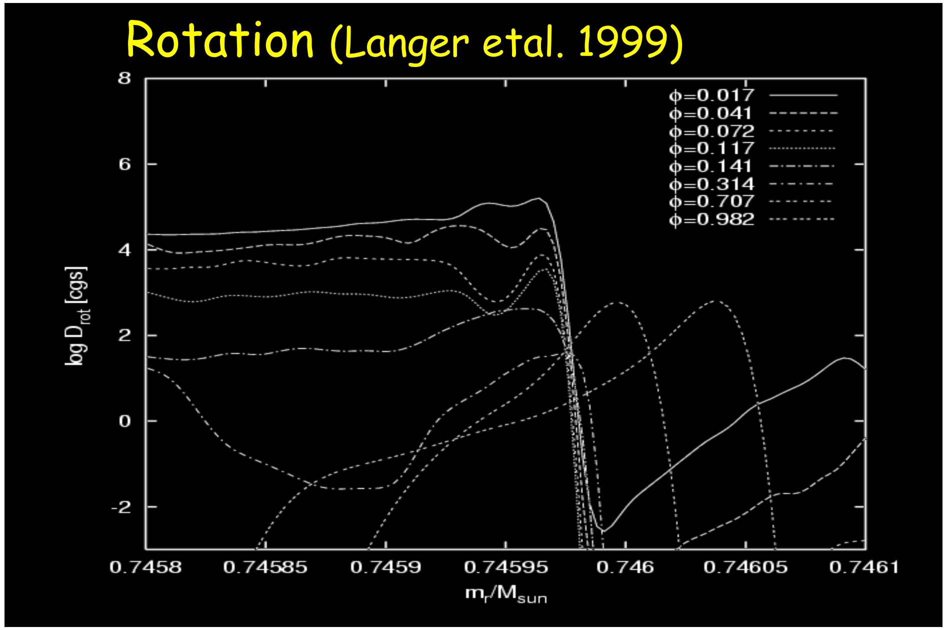
with rot mixing

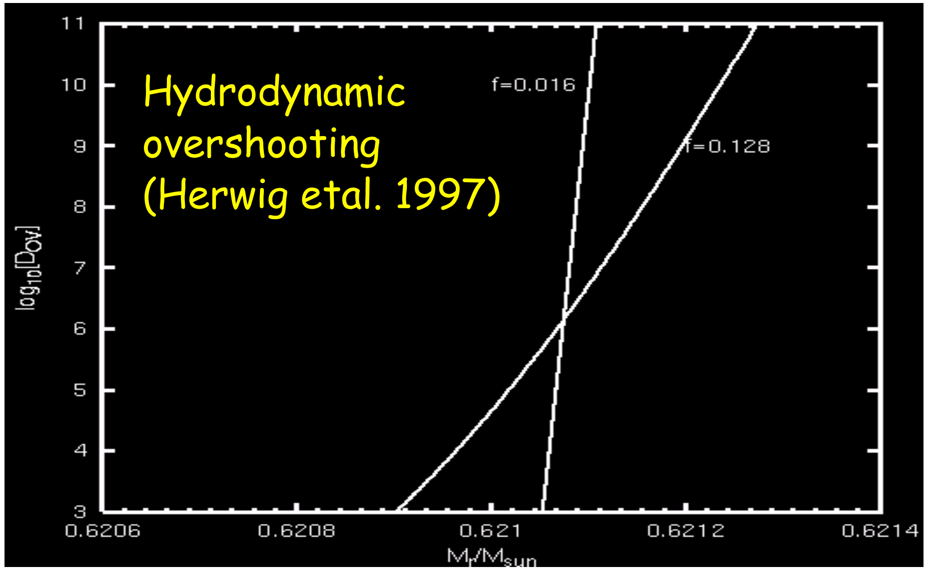


Mixing for the ^{13}C pocket

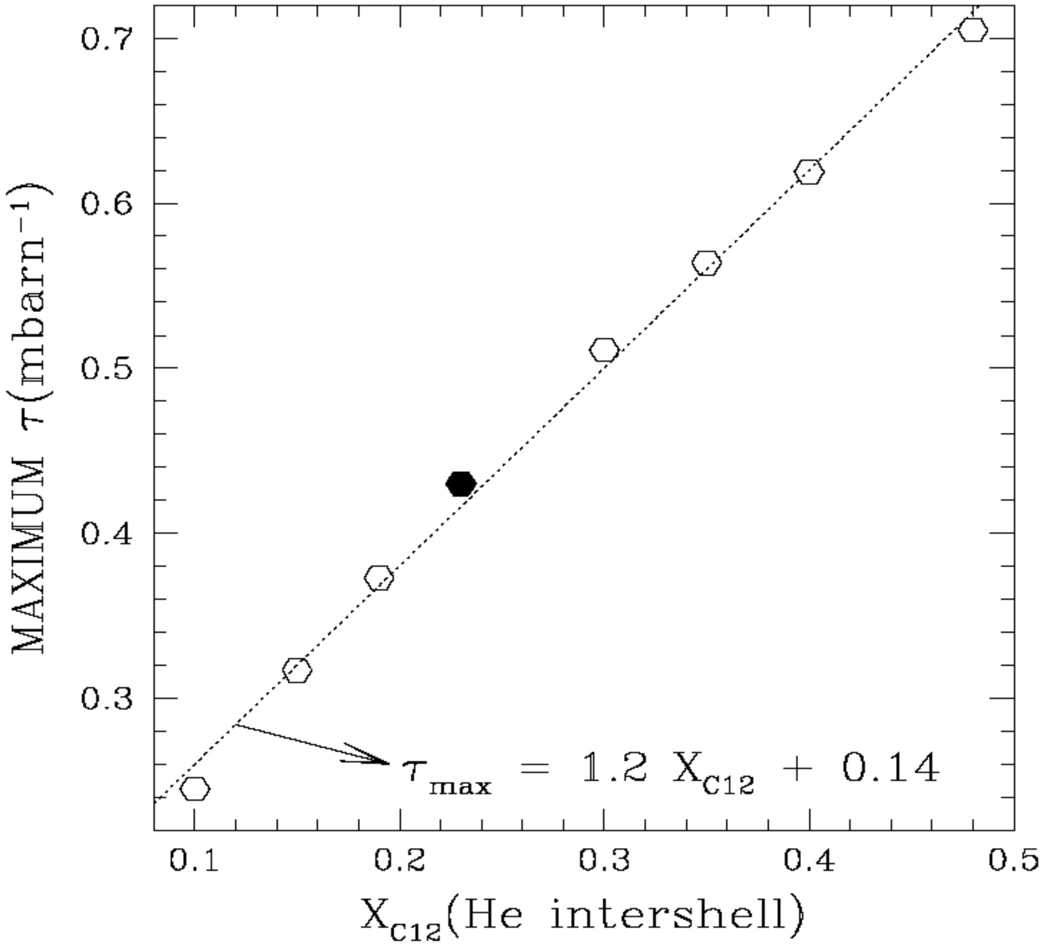
Mixing processes for the radiative s-process (partial mixing of protons with ^{12}C at the base of the convective envelope during/after 3DUP)







Intershell C abundance vs. max neutron exposure in subsequent ^{13}C-pocket



Larger ^{12}C intershell abundance results in larger ^{13}C abundance in pocket, and thus larger max. neutron exposure.

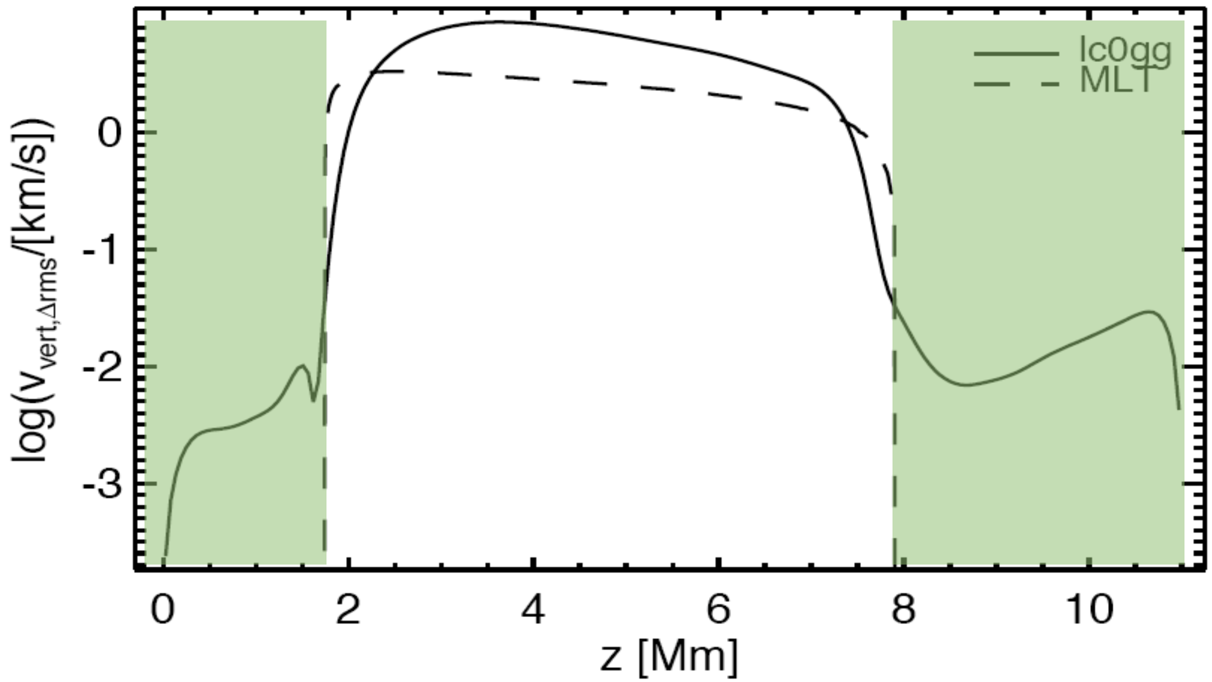
Lugaro etal. 2003

Conclusions

- Full hydrodynamic simulations of convection in AGB stars, both in the envelope and in the intershell are now becoming feasible, and offer a new exciting tool to study mixing.
- Our simulations of He-shell flash convection allow a first quantitative glimpse at mixing at and across the convective boudary.
- The simulations emphasise the need to study the role of gravity waves in much greater detail.
- Rotating models do currently not reproduce observables.

After this slide: discussion slides.

Comparison with MLT



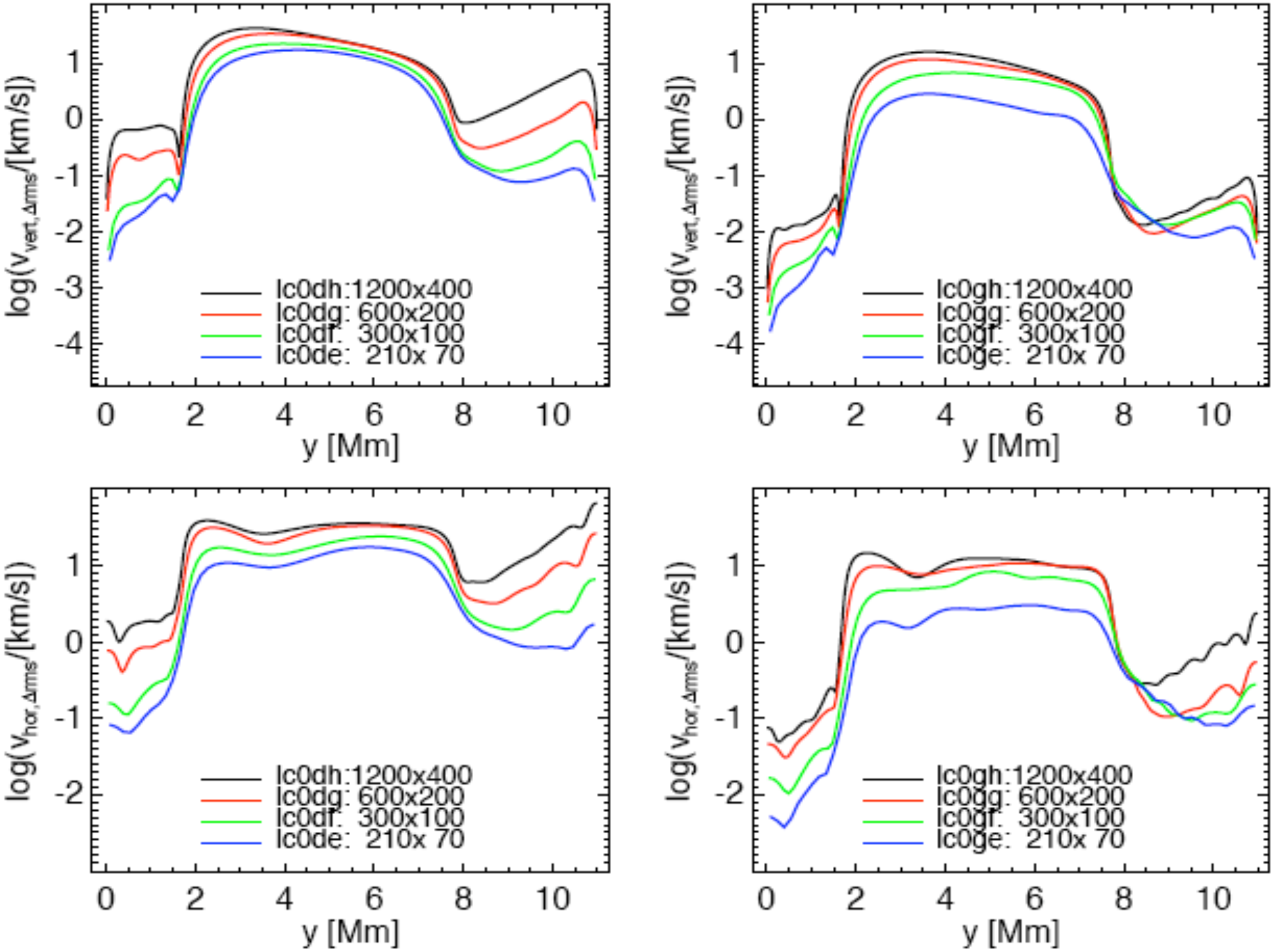
Comparison of rms-vertical velocities from hydro simulation lc0gg and the mixing-length theory velocities from the 1D-stellar evolution model.

Velocities from internal gravity waves

Convergence

vertical v

horizontal v



Driving x 30

x1

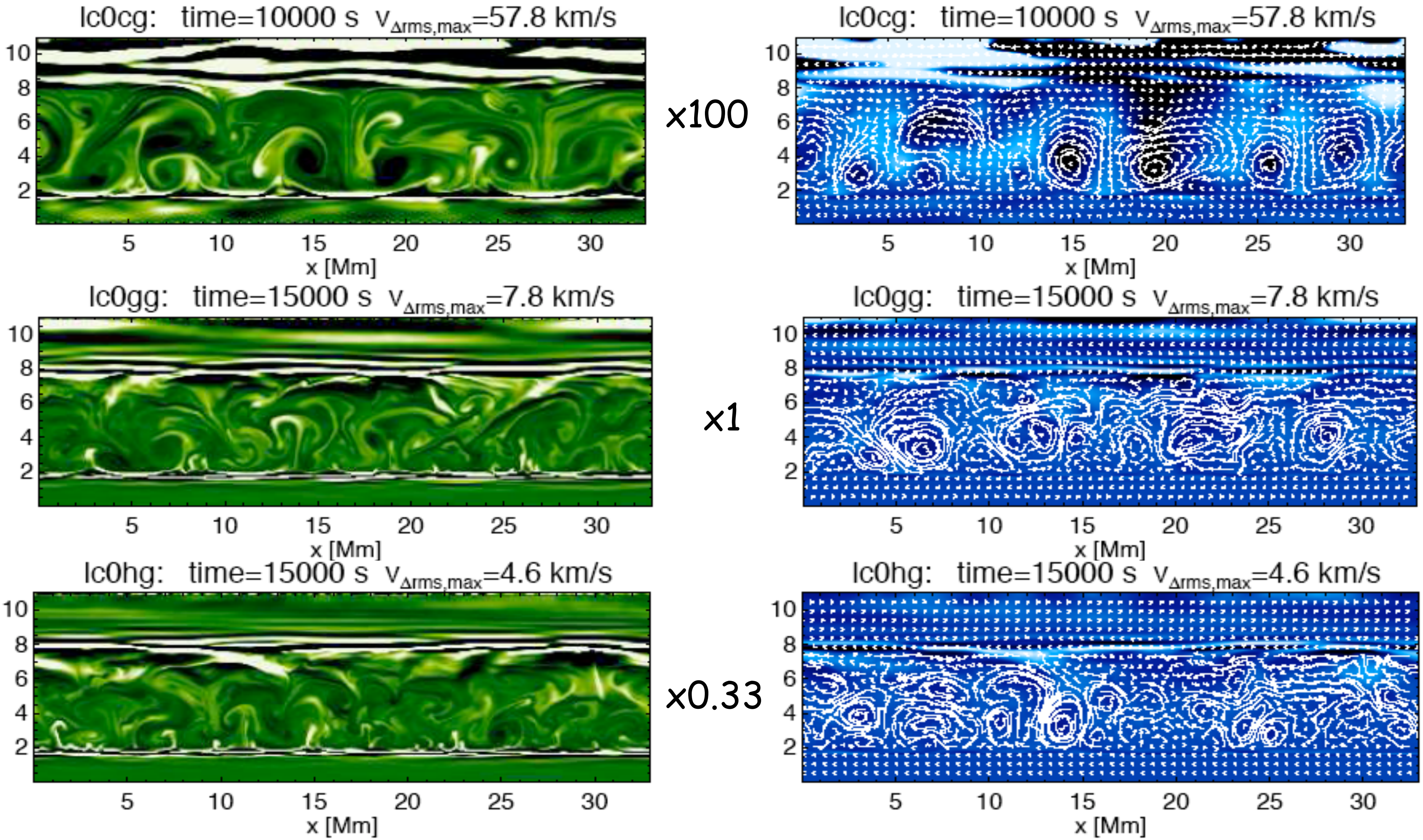
The grid

Resolution →

		e 210x70	f 300x100	g 600x200	h 1200x400	I 2400x800
c	100			10000		
d	30	10000	10000	10000	4600	900
e	10			10000		
f	3			10000		
g	1	10000	15000	16500	4300	
h	1./3.		10000	16500		
I	1./10.		10000	20000		

↑ Energy driving

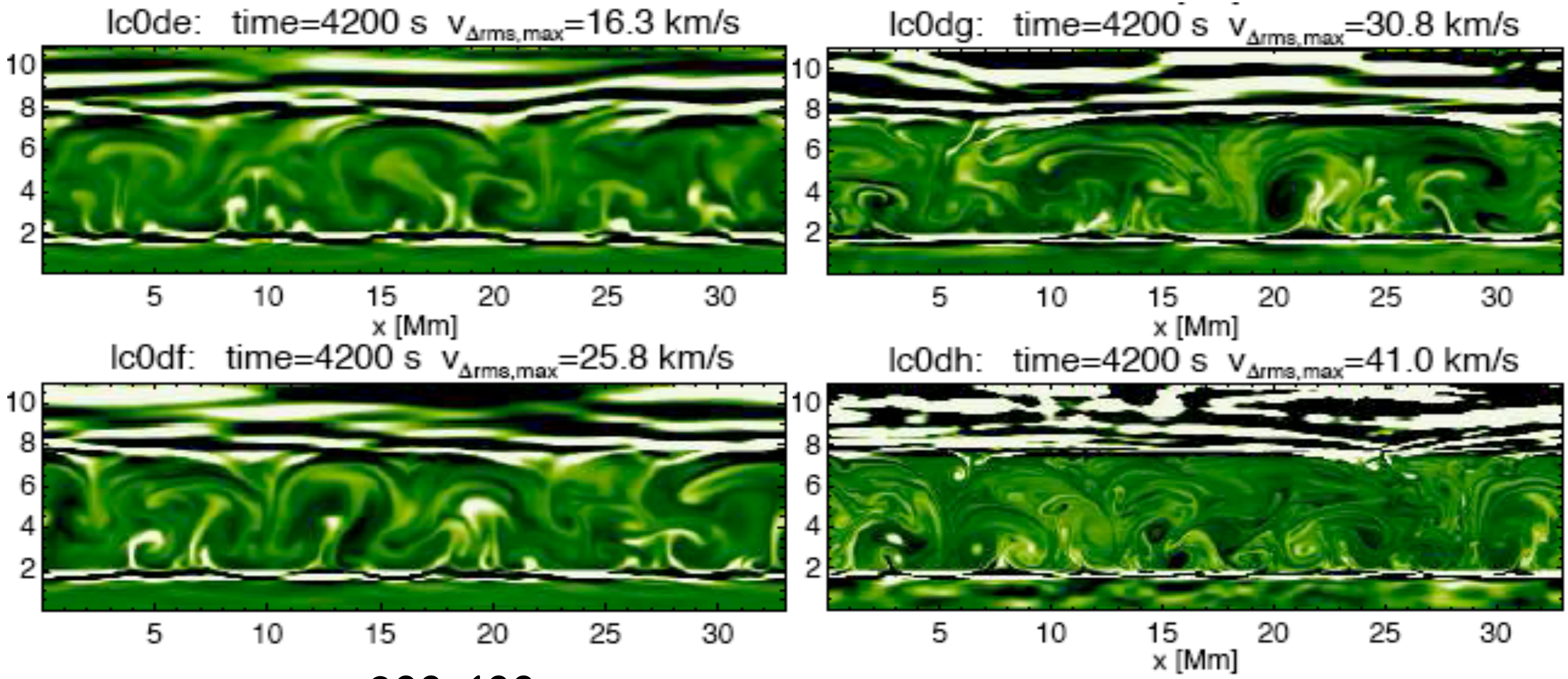
Energy-driving sequence



Resolution sequence

210x70

600x200



300x100

1200x400

Energy driving x30